
Executive Certificate in Mineral Economics

Mineral Resource Estimation

Mineral resource estimation is a multidisciplinary process that integrates geology, engineering, economics, and statistics to quantify the amount of material that can be extracted from a deposit. Understanding the terminology used throughout this process is essential for accurate communication and decision-making. The following definitions provide a comprehensive glossary of the key terms and concepts that students of the Executive Certificate in Mineral Economics must master. Each entry includes a clear definition, practical example, typical application, and common challenges that may arise in practice.

Mineral resource refers to a concentration of material of economic interest in such form, quality, and quantity that it has reasonable prospects for eventual economic extraction. Resources are reported in three confidence categories: Measured, indicated, and inferred. For example, a copper deposit with a mean grade of 0.8% Cu and an estimated tonnage of 5 million tonnes would be reported as a mineral resource, provided that the geological model and supporting data meet the required standards. The main challenge in defining a resource is ensuring that the underlying data are sufficiently reliable and that the assumptions about future extraction are realistic.

Mineral reserve is the economically mineable portion of a measured or indicated resource, after taking into account modifying factors such as mining method, recovery, dilution, and economic parameters. Reserves are also classified into proven and probable categories. A practical illustration is the conversion of a 2 million-tonne measured resource into a 1.5 Million-tonne proven reserve after accounting for a 20% dilution factor and a 10% loss factor. The primary difficulty lies in accurately modelling these modifying factors, which often require detailed engineering studies and market forecasts.

Measured resource represents the highest confidence level for a resource estimate. It is based on detailed and reliable geological and grade data, typically with close drill spacing (often less than 50 m) and thorough verification. An example would be a gold deposit where drill holes are spaced at 30 m intervals and assay results show consistent grades, allowing the geologist to assert a measured resource with a low variance. The main challenge is the cost and time required to achieve such dense sampling, especially in remote or environmentally sensitive areas.

Indicated resource is a category of resource with a lower confidence level than measured, but still sufficient for preliminary feasibility work. Data density is generally less than that required for measured resources, often with drill spacing of 50–150 m. For instance, a silver deposit may have an indicated resource based on a grid of holes spaced 100 m apart, providing enough information to support a preliminary pit design. The challenge with indicated resources is managing the higher uncertainty and ensuring that the estimate is not overly optimistic, which could lead to costly redesigns later in the project.

Inferred resource is the lowest confidence category, derived from limited geological evidence and widely spaced data, typically greater than 150 m between drill holes. An inferred resource might be reported for a lithium-bearing clay formation where only a few exploratory trenches have been sampled. The key difficulty with inferred resources is the high degree of uncertainty; they are unsuitable for detailed engineering and must be upgraded through additional exploration before they can be converted to higher confidence categories.

Cut-off grade is the minimum grade at which material can be mined profitably, considering extraction costs, processing costs, metal price, and recovery. For example, if the operating cost of a nickel mine is US\$10 per tonne and the market price of nickel is US\$20 per tonne with a recovery of 85 %, the cut-off grade can be calculated to determine the lowest acceptable nickel concentration. Determining an appropriate cut-off grade is challenging because it must reflect fluctuating commodity prices, varying operating costs, and the potential for future process improvements.

Tonnes is the unit of mass commonly used to express the quantity of material in a resource or reserve. One tonne equals 1,000 kg. In practice, a resource estimate might be presented as "3.2 Million tonnes of ore at 1.2 % Zinc." The challenge is ensuring that all mass calculations are consistent, especially when converting from volume (cubic metres) to mass, which requires accurate density values for the rock types involved.

Ore is the portion of the mineralized material that can be economically processed to extract the valuable metal or mineral. For instance, a copper deposit may contain 1.5 Million tonnes of ore with a grade of 0.9 % Cu, while the remaining material is classified as waste. Distinguishing ore from waste requires careful consideration of the cut-off grade, dilution, and mining method, which can be complex in deposits with variable geometry or steep grade gradients.

Waste is the material that must be removed or displaced to access ore but does not contain sufficient metal to be processed profitably. In an open-pit mine, waste may constitute the overburden and low-grade rock surrounding the ore body. The main challenge associated with waste is managing its volume and environmental impact, as large waste piles require stability analysis and may trigger additional permitting requirements.

Dilution refers to the inclusion of waste material into the ore stream during mining, which reduces the average grade of the ore. For example, a mining operation might experience a 15 % dilution factor if the extraction method unintentionally incorporates adjacent low-grade rock. Accurately estimating dilution is critical because it directly affects the economic viability of a project; however, predicting dilution can be difficult due to variability in mining practices and orebody geometry.

Loss is the portion of ore that is not recovered during mining, typically due to technical limitations, operational errors, or ore handling practices. A loss factor of 5 % might be applied to a resource estimate to reflect the amount of material that will be missed during extraction. While loss is often considered a fixed percentage, in reality it can vary with mining method, ore hardness, and equipment efficiency, making it a

source of uncertainty in the estimation process.

Block model is a three-dimensional representation of the mineral deposit, divided into regularly shaped cells (blocks) that each contain attributes such as grade, density, and geological classification. A typical block model might use 10 m × 10 m × 5 m blocks to represent a gold deposit, allowing the analyst to calculate the total contained metal by summing the grade of each block multiplied by its volume and density. The creation of a block model presents challenges related to data interpolation, handling of sparse data, and ensuring that the model respects geological boundaries and structural controls.

Inverse distance weighting (IDW) is a simple deterministic interpolation method that estimates the grade of unsampled locations based on the weighted average of nearby sample values, with weights decreasing with distance. For instance, IDW might be used to generate a preliminary grade surface for a silver deposit when only a limited number of drill holes are available. The limitation of IDW is its inability to model spatial variability or provide quantitative uncertainty estimates, which can lead to over- or under-estimation of grades in heterogeneous deposits.

Kriging is a geostatistical interpolation technique that provides the best linear unbiased estimate of grade at unsampled locations, incorporating both distance and spatial continuity as described by a variogram. Ordinary kriging, for example, can be applied to estimate the copper grade distribution in a porphyry deposit, producing both an estimated grade and a variance for each block. Kriging requires careful variogram modelling and assumptions about stationarity; errors in variogram selection can significantly affect the accuracy of the resource estimate.

Conditional simulation generates multiple equally probable realizations of the grade distribution, each honoring the observed data and the spatial continuity model. By producing a suite of simulated block models, analysts can assess the range of possible outcomes and quantify the uncertainty of the total contained metal. A practical use is the Monte Monte simulation of a gold deposit to evaluate the probability that the total resource exceeds a target threshold. The main challenge is the computational intensity and the need for expertise in selecting appropriate simulation parameters.

Variogram (or semivariogram) quantifies the spatial continuity of a variable by describing how the variance between pairs of samples changes with separation distance. In practice, a variogram for a nickel deposit might show a range of 200 m, indicating that samples separated by more than 200 m are essentially uncorrelated. Accurate variogram modelling is essential for geostatistical methods like kriging, but it can be difficult to achieve when data are sparse or when anisotropy (directional dependence) is present.

Spatial continuity describes the degree to which mineralization exhibits predictable patterns over space, which is a fundamental assumption in geostatistical estimation. For example, a high-grade vein system may display strong continuity along strike but abrupt changes across the dip direction. Recognizing the nature of spatial continuity helps select appropriate modeling techniques and variogram structures, yet it can be challenging to discern in complex geological settings with multiple ore-forming events.

Sample density is the number of samples (e.G., Drill holes, cores, or surface samples) per unit area or volume, influencing the confidence of the resource estimate. A dense sampling grid of 30 m × 30 m might be required for a high-grade gold deposit, whereas a lower density of 150 m × 150 m could suffice for a bulk-tonnage copper deposit. Determining the optimal sample density involves balancing exploration costs against the desired level of confidence, and misjudging this balance can lead to either unnecessary expense or insufficient data quality.

Drillhole data comprise the primary source of geological and grade information for resource estimation, including location, depth, lithology, structural measurements, and assay results. For example, a series of 150 drill holes with an average depth of 250 m may be used to delineate a polymetallic sulfide deposit. The challenge is ensuring that the drillhole data are accurately recorded, correctly oriented, and free from contamination, as errors in these data can propagate throughout the entire estimation workflow.

Assay is the laboratory analysis of a rock sample to determine its metal concentration, expressed in units such as grams per tonne (g/t) for precious metals or percent (%) for base metals. A typical assay result for a copper sample might be 0.75 % Cu. Assay accuracy depends on proper sample preparation, analytical technique, and quality control procedures; biases or analytical errors can significantly distort the resource estimate.

Geostatistics is the branch of statistics that deals with spatially correlated data, providing tools such as variograms, kriging, and simulation for resource estimation. Geostatistical methods enable the quantification of uncertainty and the incorporation of spatial continuity into grade interpolation. While powerful, geostatistics requires specialized knowledge and careful model validation; misuse can lead to overconfidence in the results or misrepresentation of the underlying geological reality.

Confidence interval in the context of resource estimation defines a range within which the true value of a parameter (e.G., Total metal tonnage) is expected to lie with a specified probability, often 95 %. For instance, a resource might be reported as 2.5 Million tonnes at 1.1 % Zinc with a 95 % confidence interval of ±0.2 Million tonnes. Calculating reliable confidence intervals demands robust statistical methods and sufficient data, and they can be misinterpreted if the underlying assumptions are not clearly communicated.

Resource classification refers to the systematic categorization of resources into measured, indicated, and inferred based on data quality, geological understanding, and confidence levels. Classification is guided by reporting standards such as JORC, NI 43-101, or SAMREC, which prescribe criteria for each category. Accurate classification is vital for investor communication; however, the process can be subjective, especially when transitioning data from inferred to indicated status, leading to potential disputes over the reliability of the estimate.

Feasibility study is a comprehensive evaluation of the technical and economic viability of a mining project, incorporating resource estimates, mining methods, processing plant design, and financial analysis. A preliminary feasibility study might use an indicated resource to assess whether a copper mine can achieve a

positive net present value (NPV). The challenge lies in integrating uncertain resource data with cost estimates and market forecasts, as optimistic assumptions can render the study overly favorable.

Economic parameters such as metal price, operating cost, capital cost, and recovery rate directly influence the profitability of a resource and therefore its classification as a reserve. For example, a decline in the price of nickel from US\$15 per lb to US\$9 per lb may render a previously economic reserve uneconomic, necessitating re-evaluation. The volatility of commodity markets and the difficulty in forecasting future costs make the selection of appropriate economic parameters a critical and often contentious aspect of resource estimation.

Metallurgical factors encompass the behavior of the ore during processing, including recovery rates, leaching efficiency, and the need for special treatment methods. In a gold deposit, a refractory ore may only yield 60 % recovery through conventional cyanidation, requiring additional processing steps such as pressure oxidation. Accurately modelling metallurgical performance is essential for realistic resource estimates, yet it can be hampered by limited test work and variability in ore characteristics.

Environmental constraints include regulations, permitting requirements, and ecological considerations that may limit the extent of mining or impose additional costs. For instance, a protected wetland adjacent to a proposed open-pit mine might restrict the allowable pit depth, influencing the cut-off grade and overall resource size. Incorporating environmental constraints into the resource model adds complexity, as it requires interdisciplinary collaboration and the ability to model alternative scenarios.

Pit optimization is the process of determining the most profitable configuration of an open-pit mine, balancing ore extraction against waste removal while respecting slope stability and other constraints. Software such as Whittle or MineSight can be used to generate an optimal pit shell based on a block model and economic parameters. The main difficulty is that pit optimization is highly sensitive to assumptions about price, cost, and cut-off grade, and small changes can lead to markedly different pit designs.

Mine design involves the detailed planning of excavation sequences, equipment selection, and infrastructure development to extract the identified reserve efficiently. A mine design for a bulk-tonnage copper operation may specify a fleet of haul trucks, excavators, and a conveyor system sized to handle a production rate of 50 kt per day. Translating a resource estimate into a practical mine design requires iterative feedback loops, as design constraints can feed back to adjust the resource model (e.g., By redefining dilution or loss factors).

Sensitivity analysis examines how changes in key inputs—such as metal price, operating cost, or recovery—affect the economic outcome of a mining project. By varying the price of zinc within a range of US\$1.00 To US\$1.40 Per lb, analysts can assess the robustness of the project's NPV. Sensitivity analysis helps identify the most critical variables, but it can be limited if the range of variation does not capture extreme market scenarios or if interactions between variables are ignored.

Risk assessment evaluates the probability and consequence of adverse events that could impact the

project's success, including geological risk, commodity price risk, and regulatory risk. A risk matrix might assign a high probability to grade uncertainty and a moderate impact to future environmental permitting delays. Effective risk assessment requires quantitative data and transparent assumptions; however, uncertainties in risk quantification often lead to reliance on qualitative judgments, which can reduce the credibility of the assessment.

Data quality encompasses the accuracy, precision, completeness, and reliability of the data used in resource estimation. High-quality data are characterized by low analytical error, proper documentation, and consistent sampling methods. For example, a dataset that includes verified assay values, georeferenced drillhole collars, and comprehensive lithology logs would be considered high quality. Maintaining data quality is challenging due to field conditions, equipment limitations, and human error, and poor data quality can undermine the entire estimation effort.

QA/QC (Quality Assurance/Quality Control) procedures are systematic processes designed to ensure that data collection, laboratory analysis, and data handling meet predefined standards. Typical QA/QC measures include the insertion of duplicate samples, blanks, and certified reference materials into the assay workflow. Robust QA/QC helps detect analytical bias and random error, increasing confidence in the assay results. Implementing QA/QC can be resource-intensive, and inadequate procedures may result in undetected errors that propagate through the resource model.

Data verification involves cross-checking and validating the integrity of the data before they are used in the estimation workflow. This may include reconciling drillhole coordinates with field notes, confirming assay units, and ensuring that geological interpretations are consistent across datasets. An example is the verification of a drillhole's depth using both downhole survey data and surface GPS records. The challenge lies in the time required to perform thorough verification, especially when data originate from multiple contractors or legacy sources.

Grade control is the practice of monitoring and adjusting mining operations to ensure that the ore being extracted meets the expected grade specifications. Real-time sampling of the ore feed and comparison with the block model allow operators to identify deviations and take corrective action. For instance, a sudden drop in copper grade may trigger a review of the mining sequence or a re-assessment of the dilution factor. Effective grade control requires rapid analytical turnaround and reliable models; delays or inaccuracies can result in significant economic losses.

Resource update is the periodic re-evaluation of a resource estimate to incorporate new data, changes in economic assumptions, or modifications to the mining plan. An annual resource update might integrate additional drillholes, updated metal prices, and revised recovery rates. The main difficulty is ensuring that updates are performed consistently and that historical data are retained for comparison, as discontinuities can obscure trends and affect stakeholder confidence.

Exploration risk refers to the uncertainty associated with the discovery and delineation of a mineral deposit,

encompassing geological, technical, and financial components. A high exploration risk may be present in frontier regions where geological data are sparse and infrastructure is lacking. Quantifying exploration risk often involves probabilistic models and scenario analysis. The challenge is balancing the potential reward of a high-grade discovery against the probability of failure, which can influence investment decisions and project financing.

Depletion is the reduction in the quantity of ore remaining as mining progresses, impacting future production rates and economic forecasts. In a long-life mine, depletion may be modelled using a depletion curve that reflects the rate at which ore is extracted each year. Accurately forecasting depletion is essential for cash-flow modelling, but uncertainties in reserve conversion and mining recovery can make depletion predictions volatile.

Mine life is the total duration over which a mining operation is expected to produce ore, typically expressed in years. A mine life of 20 years may be projected based on the current reserve estimate, planned production schedule, and anticipated depletion rate. Extending mine life often requires additional exploration to upgrade inferred resources to higher confidence categories or to discover new extensions of the deposit. The challenge lies in aligning long-term financial planning with the inherent uncertainties of resource estimation and market conditions.

Resource modeling software provides tools for building geological models, performing grade interpolation, and generating block models. Common platforms include Leapfrog, Micromine, and Surpac. These applications often integrate GIS capabilities, allowing users to visualize spatial relationships and perform pit optimization. While software streamlines many tasks, it also introduces risks related to model parameter selection, data import errors, and user bias; thorough training and validation are essential to mitigate these issues.

GIS integration (Geographic Information System) enables the combination of spatial data such as topography, land use, infrastructure, and geological information into a unified framework. GIS can be used to assess access routes, proximity to power lines, and environmental sensitivities, informing both the resource model and the mine design. The main challenge is ensuring that different data layers share a common coordinate reference system and that data resolution is appropriate for the scale of analysis.

Geological modeling is the process of constructing a three-dimensional representation of the rock units, structures, and mineralization based on field observations, drillhole data, and geophysical interpretations. A geological model may delineate the boundaries of a sulfide horizon, the orientation of faults, and the distribution of alteration zones. Accurate geological modeling is critical for defining the orebody shape and for guiding grade interpolation; however, complex geology can lead to ambiguous interpretations, requiring iterative refinement and expert judgment.

Structural modeling focuses on representing faults, folds, shear zones, and other deformation features that may influence ore distribution and mining stability. For example, a fault that offsets a copper mineralization

zone by 50 m may be incorporated into the block model to avoid over-estimation of ore continuity across the fault plane. Structural modeling adds complexity to the resource estimation workflow, as it demands precise mapping and often requires specialized software to handle discontinuities and anisotropic variograms.

Lithology describes the rock type or composition of geological units, such as granite, basalt, or sedimentary shale. Lithological mapping helps predict the distribution of ore-bearing rock versus waste rock, influencing density values and mining methods. In a polymetallic deposit, certain lithologies may be associated with higher grades of sulfide mineralization. The difficulty lies in correctly correlating lithological boundaries with grade data, especially when drilling encounters mixed or transitional rock types.

Alteration refers to the chemical and mineralogical changes in rocks caused by hydrothermal fluids, often serving as a pathfinder for mineralization. Detecting alteration zones through geochemical sampling or remote sensing can guide drilling programs. For instance, a widespread argillic alteration halo may indicate the proximity of an epithermal gold system. Interpreting alteration patterns requires expertise, and misinterpretation can lead to drilling in non-productive zones, increasing exploration costs.

Mineralization is the process by which metals are concentrated in the rock, forming ore deposits. Describing the style of mineralization—such as porphyry, VMS, or sediment-hosted—provides insight into the geometry and grade distribution of the deposit. A porphyry copper system typically exhibits a large, low-grade halo surrounding a higher-grade core. Understanding mineralization controls is essential for accurate resource modelling, yet complex multi-stage mineralization events can obscure the spatial relationship between grade and geology.

Deposit type categorizes mineral deposits based on their genesis, morphology, and typical metal associations. Recognizing the deposit type assists in selecting appropriate exploration techniques and estimation methods. For example, a lateritic nickel deposit may require shallow drilling and bulk-tonnage estimation methods, whereas a vein-type gold deposit necessitates high-density drilling and detailed structural modelling. Misclassifying the deposit type can result in inappropriate modelling approaches and inaccurate resource estimates.

Geochemistry involves the analysis of chemical elements in rocks, soils, waters, and vegetation to identify anomalies that may indicate underlying mineralization. Geochemical surveys can delineate a nickel anomaly in lateritic soils, prompting targeted drilling. The challenge lies in distinguishing between pathfinder elements and background concentrations, as well as accounting for surface alteration and weathering effects that can modify the geochemical signature.

Geophysics employs physical methods such as magnetic, gravity, electromagnetic, and seismic surveys to image subsurface structures and infer the presence of ore bodies. A magnetic anomaly may highlight the location of an iron-oxide deposit, while an induced polarization (IP) response can indicate disseminated sulfides. Integrating geophysical data with drillhole information enhances model confidence, but

interpreting geophysical signatures can be ambiguous, requiring multiple data types and expert judgment.

Sampling error is the discrepancy between the true grade of the material and the measured grade obtained from a sample, arising from heterogeneity, sample size, or analytical imprecision. For a highly variable gold deposit, a 2-kg bulk sample may not accurately represent the grade of the surrounding rock, leading to significant sampling error. Quantifying sampling error is essential for uncertainty analysis, yet it can be difficult to separate from analytical error without extensive replicate sampling.

Bias in resource estimation refers to systematic deviations from the true value, often introduced by methodological choices, data selection, or subjective judgment. An optimistic bias may result from over-estimating recovery rates, while a pessimistic bias could stem from applying an excessively high cut-off grade. Identifying and correcting bias requires independent review and sensitivity testing; however, biases can be subtle and may persist unnoticed, affecting the credibility of the estimate.

Validation is the process of checking the resource model against independent data or external benchmarks to ensure its reliability. Validation techniques include cross-validation of variograms, comparison with historical production data, and independent peer review. A well-validated model increases stakeholder confidence, but achieving validation can be resource-intensive, especially when independent data are scarce or when the model incorporates numerous complex parameters.

Reporting standards such as the JORC Code, NI 43-101, and SAMREC provide guidelines for the disclosure of mineral resources and reserves, ensuring consistency, transparency, and comparability across projects. These standards define the required level of confidence for each resource category, specify the necessary documentation, and outline the responsibilities of qualified persons. Compliance with reporting standards is mandatory for public disclosures, yet interpreting the standards can be challenging, especially when local regulations impose additional requirements.

Disclosure involves the communication of resource and reserve information to investors, regulators, and the public, adhering to the applicable reporting standards. Effective disclosure includes clear presentation of the methodology, assumptions, and uncertainties. For example, a technical report may disclose that the resource estimate is based on ordinary kriging with a 95 % confidence interval. The main difficulty is balancing the need for transparency with the protection of proprietary information, particularly in competitive mining jurisdictions.

Stakeholder communication refers to the ongoing dialogue with parties interested in the project, such as local communities, government agencies, investors, and employees. Communicating resource estimates in a clear and understandable manner helps build trust and facilitates permitting processes. Challenges include translating technical concepts into lay language and addressing concerns about environmental impact and economic benefits.

Legal framework encompasses the national and regional laws governing mineral rights, exploration permits, environmental assessments, and mining contracts. Understanding the legal framework is essential for

determining ownership of the resource, royalty obligations, and compliance requirements. For instance, a mining jurisdiction may require that all resource estimates be audited by a certified professional engineer before a mining lease can be issued. Navigating complex legal regimes can be time-consuming and may affect project timelines.

Ownership defines the rights to explore, develop, and profit from a mineral deposit, which can be held by a single company, a joint venture, or a state entity. Ownership structures influence the allocation of costs, revenues, and decision-making authority. In a 70-30 joint venture, the partner with 30% ownership may be entitled to 30% of the net cash flow, but also share 30% of the development costs. Clarifying ownership arrangements early helps avoid disputes during the resource estimation and development phases.

Confidentiality protects sensitive information related to the resource estimate, such as undisclosed drillhole locations, proprietary modelling techniques, or strategic plans. Confidentiality agreements are often used between exploration companies and consultants to safeguard competitive advantage. However, excessive confidentiality can hinder investor confidence, as stakeholders may demand transparency under reporting standards. Striking the right balance between protection and disclosure is a recurring challenge in the mining industry.

Grade is the concentration of the target metal or mineral within the ore, expressed in units such as grams per tonne (g/t) for gold or percent (%) for copper. Grade is a primary driver of economic viability; higher grades typically translate to lower processing costs per unit of metal produced. For example, a gold deposit with an average grade of 5 g/t will generate more revenue than one with 1 g/t, assuming similar mining costs. Accurate grade estimation is difficult in deposits with strong spatial variability, and errors can have a large impact on the projected cash flow.

Recovery denotes the proportion of the metal that can be successfully extracted from the ore during processing, often expressed as a percentage. Recovery rates depend on ore mineralogy, processing technology, and operational efficiency. A copper plant achieving 85% recovery will produce more metal from the same amount of ore than a plant with 70% recovery. Estimating recovery accurately requires metallurgical test work; uncertainties in recovery can lead to misclassification of resources and reserves.

Density is the mass per unit volume of rock, typically measured in tonnes per cubic metre (t/m^3). Density values are used to convert volumes derived from geological models into tonnages. For instance, a granite host rock may have a density of 2.7 T/m^3 , while a massive sulfide may be 5.0 T/m^3 . Incorrect density assumptions can cause systematic errors in tonnage calculations, especially when the deposit contains a mixture of high-density and low-density lithologies.

Volume represents the three-dimensional space occupied by the orebody, measured in cubic metres or cubic feet. Volume is derived from the geometric interpretation of the geological model and is a fundamental input for converting to tonnage using density. For example, a modeled orebody of 1.2 Million m^3 with an average density of 2.8 T/m^3 yields approximately 3.36 Million tonnes of material.

Accurately delineating volume is challenging in irregularly shaped deposits, where subjective decisions about boundaries can significantly affect the final estimate.

Interpolation is the mathematical process of estimating unknown values (such as grade) at unsampled locations based on known sample data. Common interpolation techniques include inverse distance weighting, kriging, and spline methods. Interpolation is essential for constructing continuous grade surfaces from discrete drillhole assays. Selecting an inappropriate interpolation method or incorrectly specifying its parameters can introduce bias or excessive smoothing, leading to inaccurate resource estimates.

Extrapolation extends the grade model beyond the area covered by data, often to infer the presence of ore in unsampled zones. While sometimes necessary, extrapolation carries high uncertainty because it relies on assumptions about continuity that may not hold outside the data envelope. For example, projecting a high-grade zone beyond the limits of a drill program without additional verification can result in overestimation of resources.

Variance quantifies the dispersion of grade values around the mean, providing a measure of uncertainty in the estimation. In geostatistics, the kriging variance is used to assess the reliability of each block's grade estimate. A block with a high variance indicates greater uncertainty and may be targeted for additional sampling. Understanding variance is crucial for risk analysis, yet interpreting variance values requires statistical expertise and clear communication to non-technical stakeholders.

Standard deviation is the square root of variance, offering a more intuitive measure of spread in the same units as the grade. Reporting the standard deviation alongside the mean grade helps convey the level of confidence in the estimate. For example, a gold grade of 2.5 G/t $\pm$ 0.3 G/t (standard deviation) provides a clearer picture of variability than a single point estimate. However, standard deviation assumes a normal distribution, which may not be appropriate for highly skewed grade distributions common in precious-metal deposits.

Bias correction involves adjusting the resource estimate to account for known systematic errors, such as assay drift or sampling under-representation of high-grade zones. Bias correction can be performed using statistical techniques or by incorporating additional data. For instance, if assay results are found to be consistently low by 5 % based on reference standards, a bias correction factor can be applied to all grades. The difficulty lies in accurately identifying the source and magnitude of bias, as over-correction can introduce new errors.

Monte Monte simulation is a stochastic technique that generates a large number of random scenarios to assess the probability distribution of an outcome, such as total metal tonnage. By repeatedly sampling from the grade distribution and applying economic parameters, analysts can estimate the likelihood of achieving a target NPV. Monte Monte simulations are valuable for decision-making under uncertainty, but they require substantial computational resources and careful definition of input distributions to avoid misleading results.

Scenario analysis explores the impact of alternative assumptions on the resource estimate and project economics. Typical scenarios might include variations in metal price, recovery, operating cost, or mining method. Scenario analysis helps stakeholders understand the range of possible outcomes and identify key drivers of project success. The challenge is selecting realistic scenarios and communicating the results without overwhelming decision-makers with excessive detail.

Cut-off elevation is the vertical limit in an open-pit model that separates ore from waste based on the cut-off grade and the economic parameters. Determining the cut-off elevation involves iterative pit optimization to maximize the net present value of the mine. For a copper deposit, the cut-off elevation may be set at 250 m above sea level, defining the top of the profitable pit shell. Adjustments to the cut-off elevation can have a profound effect on the size of the resource classified as ore, making its accurate determination essential.

Bench refers to the horizontal level or step in an open-pit mine, created to provide access to the ore and waste zones. Bench design influences the mining sequence, equipment selection, and overall safety. For example, a 10 m bench height may be chosen for a bulk-tonnage operation to accommodate large haul trucks. Designing benches requires integrating geological data, slope stability analysis, and operational constraints; errors in bench design can lead to inefficient extraction and increased dilution.

Strip ratio is the ratio of waste material removed to ore extracted, expressed as a dimensionless number (e.g., 2 : 1). A lower strip ratio indicates a more economical mine, as less waste needs to be moved per unit of ore. For instance, an open-pit copper mine with a strip ratio of 1.5 : 1 will have lower haulage costs than a mine with a strip ratio of 3 : 1. Estimating the strip ratio accurately depends on reliable waste and ore delineation in the block model, and uncertainties can significantly affect project economics.

Pit slope is the angle at which the walls of an open-pit mine are designed to remain stable, expressed in degrees or as a horizontal-to-vertical ratio (e.g., 1 : 1). The allowable pit slope is governed by rock mechanics, geotechnical investigations, and safety regulations. A steeper pit slope reduces the amount of waste that must be removed, improving the strip ratio, but may increase the risk of wall failure. Determining the optimal pit slope requires balancing economic benefits against geotechnical constraints and regulatory requirements.